ERDC/CRREL TR-01-3

Cold Regions Research and Engineering Laboratory

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Engineer Research and Development Center

Design of Freezing Bed for Sludge Dewatering at McMurdo, Antarctica

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February 2001

REPORT DOCUMENTATION PAGE

1. REPORT DATE (DD-MM-YYYY) 01-02-2001	**2. REPORT TYPE** Technical Report
3. DATES COVERED (FROM - TO) xx-02-2001 to xx-02-2001	
4. TITLE AND SUBTITLE Design of Freezing Bed for Sludge Dewatering at McMurdo, Antarctica Unclassified	**5a. CONTRACT NUMBER**
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S) Martel, James C ;	**5d. PROJECT NUMBER**
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME AND ADDRESS U.S. Army Engineer Research and Development Center Cold Regions Research and Engineering Laboratory 72 Lyme Road Hanover , NH 03755-1290	**8. PERFORMING ORGANIZATION REPORT NUMBER** ERDC/CRREL-TR-01-03
9. SPONSORING/MONITORING AGENCY NAME AND ADDRESS National Science Foundation 4201 Wilson Blvd. Arlington , VA 22230	**10. SPONSOR/MONITOR'S ACRONYM(S)**
	11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
A
PUBLIC RELEASE

National Science Foundation
4201 Wilson
Blvd.

Arlington , VA 22230
13. SUPPLEMENTARY NOTES
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15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON**
a. REPORT Unclassified	**b. ABSTRACT** Unclassified	**c. THIS PAGE** Unclassified	Public Release	13	Rike, Jack jrike@dtic.mil
					19b. TELEPHONE NUMBER **International Area Code** **Area Code Telephone Number** **DSN**

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February 2001

Prepared for
NATIONAL SCIENCE FOUNDATION

PREFACE

This report was prepared by Dr. C. James Martel, Environmental Engineer, Geochemical Sciences Division, Cold Regions Research and Engineering Laboratory (CRREL), U.S. Army Engineer Research and Development Center (ERDC), Hanover, New Hampshire.

Funding for this project was provided by the National Science Foundation (NSF), Office of Polar Programs, Polar Research Support Section, under an interagency agreement.

Technical reviews were provided by George Blaisdell and Dr. Daniel J. McKay, both of CRREL.

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Design of Freezing Bed for Sludge Dewatering at McMurdo, Antarctica

C. JAMES MARTEL

INTRODUCTION

In a report entitled, *McMurdo Research Station, Antarctica, Wastewater Treatment Alternatives Evaluation,* Consoer Townsend Envirodyne (CTE) Engineers (1999) recommend a belt filter press for sludge thickening and dewatering for McMurdo Station, Antarctica. The belt filter press technology is in common use today at many conventional wastewater treatment plants. Basically, the belt filter press consists of two continuous belts, set one above the other (Fig. 1). Conditioned sludge is fed in between the two belts, which transport it through drainage, pressure, and shear zones. The dewatered sludge is then removed by a scraper. The components of this type of sludge dewatering unit include: a belt and roller press system, a polymer feed system, polymer storage equipment, sludge feed pumps, an odor scrubbing system, and wash water pumps. Typically, a belt press is capable of producing a sludge with a 10 to 15% solids content (85 to 90% liquid).

Given McMurdo's location at approximately 77º50' south latitude, a treatment plant designed to use the natural freeze–thaw process to dewater the sludge may be a better choice than a belt filter press. Freezing beds have proven to be effective at many treatment plants located in Alaska, the northern U.S., and Canada (Martel 1998). A conceptual sketch of a freezing bed is shown in Figure 2. An actual freezing bed at Fort McCoy, Wisconsin, is shown in Figure 3. It consists of a rectangular in-ground concrete structure with a ramp at one end and a sump at the other. The ramp is used to provide vehicle access for sludge removal. The sump is used to collect the meltwater from the bed via the underdrain system and return it back to the head of the plant for further treatment. The underdrain system consists of a series of drain pipes covered by an 8- to 10-cm-thick layer of sand. The bed is covered with a roof and surrounded by a snow fence to keep snow from accumulating in the bed. Snow should be kept out of the bed because it insulates the sludge and reduces the rate of freezing. Without this protection, the predictability and performance of the process is reduced because of the annual variability in snow accumulations.

According to Martel and Diener (1991), the freezing bed is capable of dewatering aerobically digested sludge to a 24.5% solids content, which is approximately twice the solids content of the sludge produced by a typical filter press system. Using the freezing bed system could reduce by one-half the volume of sludge needing to be returned to the U.S. from McMurdo. Other advantages of the freeze bed technology include:

- Less energy consumption, since nature does the freezing and thawing.
- No requirement for conditioning chemicals.
- Minimal odors because the low temperatures limit biological activity.
- Simple operation and maintenance.

The mechanism that dewaters the sludge is freezing during the winter months and thawing during the spring and summer. During the winter freezing period, ice crystals grow by adding water molecules to their structure. All other impurities, including sludge particles, are rejected and thus become clumped together into larger particles. During the spring and summer, the ice crystals thaw, and the meltwater drains between and through the joined particles, leaving a solid material with high solids content.

This report evaluates freezing bed technology, for use at McMurdo, to dewater the aerobically digested sludge produced by the proposed secondary treatment

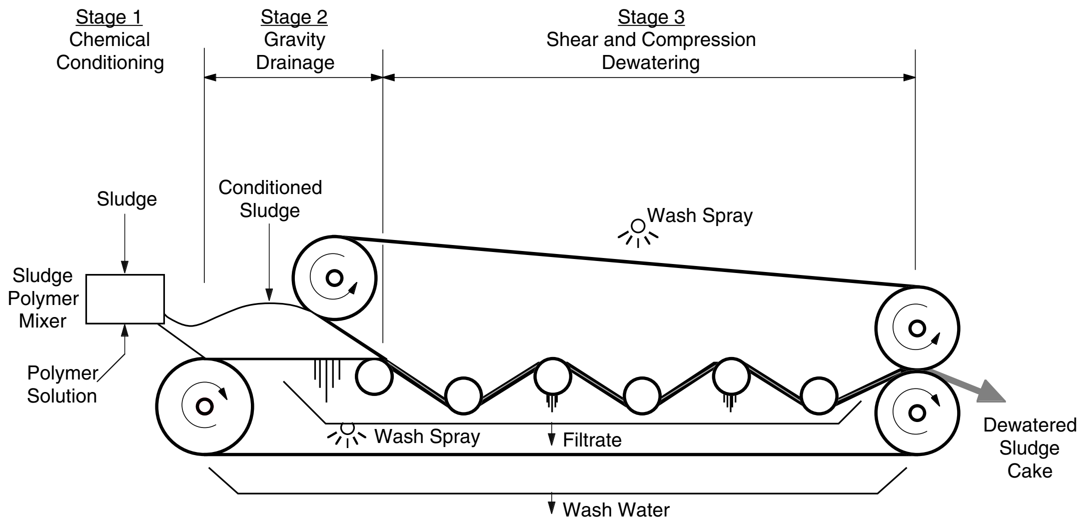

Figure 1. Schematic of belt filter press.

plant. A preliminary design is developed here that is based on average climatic data at McMurdo and the sludge quantities reported by CTE (1999).

DESIGN CRITERIA

Currently, wastewater generated at McMurdo only receives maceration (grinding) prior to being discharged into McMurdo Sound. Although it is not required by treaty, the goal of NSF is to provide a level of wastewater treatment consistent with the 1972 *Clean Water Act*. To achieve this goal, a secondary treatment plant will be required.

CTE Engineers evaluated several secondary treatment alternatives and recommended extended aeration followed by low pressure ultraviolet (UV) disinfection. Aerobic digestion is proposed for sludge stabilization followed by a belt filter press for dewatering. In this analysis, I assumed that all components of a treatment system would be the same except that a freezing bed would used instead of a belt filter press. The volume of sludge that needs dewatering is projected to be 178 m^3 (47,000 gal.) annually.

The horizontal dimensions of a freezing bed depend on the depth of sludge that can be frozen and thawed at the proposed site and the volume of sludge to be processed. The depth of sludge that can be frozen and thawed depends on the climatic conditions at the site. The monthly average air temperatures and insolation at McMurdo Station can be found in Table 1. These data show that the average temperature is below freezing during each month. Consequently, freezing sludge

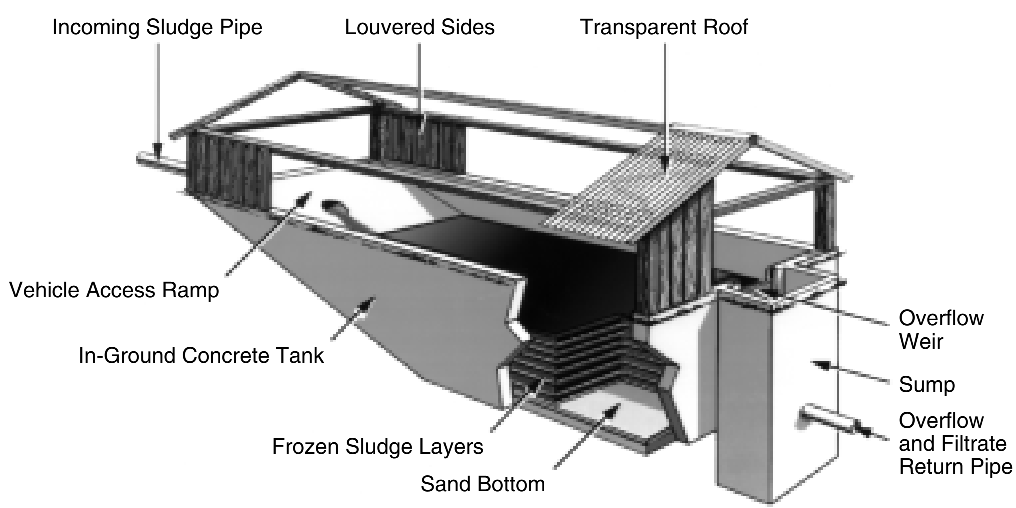

Figure 2. Conceptual drawing of freezing bed.

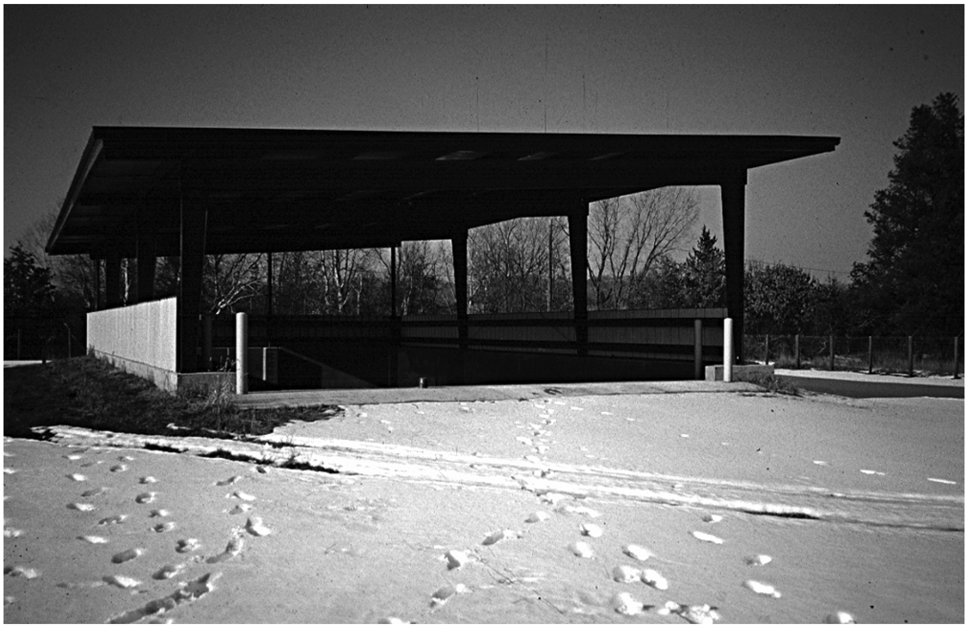

Figure 3. Freezing bed at Fort McCoy, Wisconsin.

Table 1. Monthly average air temperatures and insolation at McMurdo Station, Antarctica (after USA Today Climate 2000).*

Month	*Average high temperature (°C)*	*Average low temperature (°C)*	*Average temperature (°C)*	*Insolation (W/m²)*
January	–0.6	–5.6	–3.1	327
February	–6.1	–11.7	–8.9	180
March	–14.4	–20.0	–17.2	49
April	–17.8	–24.4	–21.1	4
May	–18.9	–26.7	–22.8	0
June	–18.9	–26.7	–22.8	0
July	–21.1	–30.0	–25.5	0
August	–22.8	–31.7	–27.2	1
September	–20.6	–28.9	–24.7	27
October	–15.5	–22.8	–19.2	119
November	–6.7	–12.8	–9.7	255
December	–1.1	–6.1	–3.6	359

*Personal Communication with J.S. Thompson, Air Force Combat Climatology Center, Asheville,North Carolina, 2000.

will not be a problem. However, thawing the sludge by air convection only will not be possible. Fortunately, there is a considerable amount of solar radiation available during the summer months.

Freezing depth

The freezing depth (D_f) can be predicted from (Martel 1989):

$$D_f = \frac{P_f (T_f - \bar{T}_{af})}{\rho_f L \left(\frac{1}{\bar{h}_c} + \frac{\varepsilon}{2K_{fs}} \right)} \qquad (1)$$

where P_f = freezing period (hr)
T_f = freezing point temperature (0°C)
$\bar{T}_{af}$ = average ambient temperature during freezing (°C)
ρ_f = density of frozen sludge (917 kg/m^3)
L = latent heat of fusion (93 W hr/kg)
$\bar{h}_c$ = convection coefficient (7.5 W/m^2 °C)
ε = thickness of each sludge layer (m)
K_{fs} = conductivity coefficient of frozen sludge (2.21 W/m °C).

Examination of Table 1 suggests a freezing period (P_f) consisting of the months of March through September, since these months have no significant solar insolation. This period is equivalent to 5136 hours. The average temperature ($\bar{T}_{af}$) during this period is –23ºC. Assuming a sludge layer thickness (ε) of 0.08 m, and substituting the remaining values into eq 1, we obtain

$$D_f = \frac{5136[0-(-23)]}{917 \times 93 \left(\frac{1}{7.5} + \frac{0.1}{2 \times 2.21} \right)} = 8.9 \text{ m.}$$

Thus, eq 1 predicts that 8.9 m of sludge can be frozen in the freezing bed during an average winter at McMurdo, assuming that sludge will be applied in 8-cm layers and that each layer would be applied as soon as the previous layer had frozen. The equation also assumes that the surface of the bed is kept free of snow.

Thawing depth

The equation for predicting the thawing design depth (Y) is (Martel 1989):

$$Y = \left[\left(\frac{K_{ss}}{\theta \bar{h}_c} \right)^2 + \frac{2K_{ss} P_{th}}{\theta \beta} \right]^{1/2} - \frac{K_{ss}}{\theta \bar{h}_c} \qquad (2)$$

where β = $\rho_f L / \bar{T}_{at} \left(\bar{T}_{at} - T_f + \alpha\tau\bar{I} / \bar{h}_c \right)$
K_{ss} = thermal conductivity of settled sludge (0.35 W/m ºC)
θ = fraction of settled sludge per unit depth of thawed sludge (0.15 for aerobically digested sludge)
P_{th} = thawing period (hr)
$\bar{T}_{at}$ = average ambient air temperature during thaw (ºC)
α = solar absorptance of the sludge (0.9)
τ = transmittance of the roof material (0.9 for fiber reinforced polyester roof)
$\bar{I}$ = average insolation during the thawing period (W/m^2).

If the months of March through September are used for freezing, then the remaining months (October through February) will be used for thawing, draining, drying, and removing the sludge for retrograde back to the U.S. Most of this time will be needed for thawing and draining, which occur simultaneously under normal operation. For this analysis, it is assumed that the thawing period (P_{th}) will include the months of October, November, December, and January (2952 hours). The average air temperature ($\bar{T}_{at}$) and insolation ($\bar{I}$) during this period are –8.9ºC and 265 W/m^2, respectively. Substituting these values into eq 2 gives

$$\beta = 917 \times 93 / (-8.9 - 0 + (0.9 \times 0.9 \times 265)/7.5)$$
$$= 4325$$

$$Y = \left[\left(\frac{0.35}{0.15 \times 7.5} \right)^2 + \frac{2 \times 0.35 \times 2952}{0.15 \times 4325} \right]^{1/2} - \frac{0.35}{0.15 \times 7.5} = 1.5 \text{ m.}$$

Thus, eq 2 predicts that only 1.5 m of sludge can be thawed during the selected thawing period. This depth is lower than would be expected in more temperate climates because of the subfreezing air temperature during the thawing period. Thawing in this case is achieved strictly by solar radiation heating.

Thawing depth with supplemental heating

According to the CTE (1999) report, the sewage effluent has a temperature of 23ºC. If this effluent was used to heat the freezing bed, the thawing depth could be increased for the October to February thawing period. One way to do this would be to build a pipe network into the concrete base of the freezing bed. Warm secondary effluent from the treatment plant could then be pumped through this network during the thawing

period. An equation for this configuration can be developed by conducting an energy balance across the pipe/sludge interface

$$q_k = e \tag{3}$$

where q_k is the rate of heat transfer by conduction and e is the rate of energy gain by the frozen sludge during the phase change.

Assuming that the pipe network will behave as a flat plate (i.e., the melting front will be uniform across the surface of the frozen sludge), and the thermal conductivity of the pipe is infinite, we can express q_k as (Kreith 1973)

$$q_k = \frac{K_{ss} A}{\Delta}\left(\overline{T}_s - T_f\right) \tag{4}$$

where A = surface area
Δ = thickness of the settled solids
$\overline{T}_s$ = average temperature of the pipe surface.

The rate of energy transfer to the frozen sludge during the phase change can be calculated from (Kreith 1973)

$$e = \rho_t LA \frac{dy}{dt} \tag{5}$$

where dy/dt is the rate change in the position of the freeze–thaw interface.

Substituting eq 4 and 5 into eq 3 results in the following energy balance relationship

$$\frac{K_{ss}}{\Delta}\left(\overline{T}_s - T_f\right) = \rho_f L \frac{dy}{dt}. \tag{6}$$

If the solids are uniformly distributed in the frozen sludge, then the thickness of the settled solids layer (Δ) can be expressed as θy, where θ is the fraction of settled solids per unit depth of thawed sludge and y is the depth of thawed sludge. Making this substitution, we see that eq 6 becomes

$$\frac{K_{ss}}{\theta y}\left(\overline{T}_s - T_f\right) = \rho_f L \frac{dy}{dt}. \tag{7}$$

Separating variables and integrating dt from 0 to P_{th} (the thawing period) and dy from 0 to Y (the total depth of thawed sludge) gives the general equation for predicting the thawing depth in this case

$$Y = \left[\frac{2K_{ss}P_{th}\left(\overline{T}_s - T_f\right)}{\rho_f L\theta}\right]^{1/2}. \tag{8}$$

To calculate Y, I assumed an average temperature of 20°C at the surface of the sludge ($\overline{T}_s$). This assumption is conservative because the average temperature of the effluent is 23°C. The thawing period (P_{th}) is 2972 hours, which occurs during the months of October, November, December, and January. A previous study (Martel 1989) determined that the constants k_s and θ are 0.35 W/m °C and 0.15, respectively. Substituting these values into eq 8 results in a predicted thawing depth of 3.2 m.

Design depth

The depth of the freezing bed depends on the depth of sludge that can be frozen and thawed during an annual freeze–thaw cycle. In this case, the energy balance equations predict that the depth of sludge that can be frozen will be significantly more than the depth of sludge that can be thawed. Therefore, the thawing depth will govern freezing bed design depth. Using solar energy alone gives a design depth of 1.5 m. Using waste heat from the effluent gives a design depth of 3.2 m. A combination of both thawing methods would result in a design depth of 4.7 m.

From an economic point of view, it is tempting to use a design depth of 4.7 m because of a resulting reduction in bed size. However, I am not aware of any freezing beds that have been built to that depth. The maximum design depth used in full scale beds that have been built in Alaska is 2.0 m. Also, construction of a freezing bed with walls high enough to freeze 4.7 m of sludge may require special construction practices. Therefore, I suggest that a freezing bed be built with a design depth not in excess of 2.0 m. For McMurdo, I recommend a design depth of 1.5 m with provision for an additional 0.5 m provided by supplemental thawing with waste heat. This configuration will provide the greatest flexibility of operation in that it allows more than one thawing method and provides additional capacity.

FREEZING BED SIZE

The bed size can be calculated now that the design depth and annual sludge production rate are known. I assumed a total bed depth of 2.0 m (1.5 m frozen sludge plus 0.5 m additional capacity) and a bed width of 10 m. Using an access ramp slope of 3:1, I calculated the length of the bed to be 16 m (Fig. 4). Thus, the total area occupied by the bed would be 160 m^2. For relative scale, this bed size is approximately 30% larger than the freezing bed at Fort McCoy. Of course, other dimensional combinations are possible as long as the design depth and annual sludge volume requirements are met.

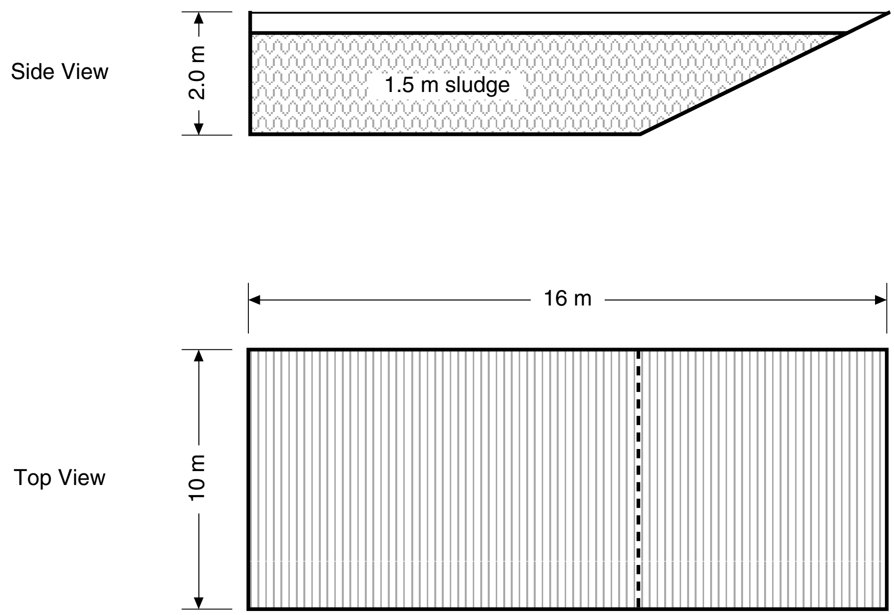

Figure 4. Dimensional sketch of freezing bed for McMurdo.

DISCUSSION

The design features of the McMurdo freezing bed would be essentially the same as a conventional freezing bed except for the louvered sides. The louvered sides allow outside air to freely enter the bed and accelerate the freezing process. However, for this application, freezing is not a problem. Instead of the louvered sides, it would be beneficial to construct insulated solid walls to retain heat during the thawing process. The insulated walls will likely slow the freezing process during winter but, because of the significant excess freezing capacity, it should not be enough to reduce the freezing design depth to something less than the thawing design depth.

A critical component of this freezing bed is the transparent roof. Without it, the sludge will not thaw unless a supplemental heating system is activated. To take full advantage of the sun, the bed should be oriented towards it, and the roof should be pitched to allow entry of low angle solar radiation.

Since poured-in-place concrete structures are generally not feasible at McMurdo, it is likely that the bed would be prefabricated in the U.S. or New Zealand. The bottom could be made from pre-cast concrete panels and the sides could be made from plates of insulated steel that are bolted together in a way that is similar to a water tank. A pipe network for thawing should be incorporated into the concrete floor panels. Also, the concrete panels should be cast with a minimum of three or four channels (one along each side of the bed and one or two in the middle) to provide a pathway for the drain pipes. The bottom of the bed, including the drain pipes, should be covered with approximately 15 cm of sand to collect meltwater and convey it to the drain pipes.

To use the bed, the operator would begin applying sludge by early March. Since most of the sludge will be generated during the summer months, it may necessary to provide extra capacity in the aerobic digester or to construct a temporary storage tank. Sludge would be applied to the bed directly from the aerobic digester or storage tank in sequential 8- to 10-cm layers. Each layer will be frozen completely before the next layer is applied. CRREL has developed a device called the Automatic Sludge Applicator that automatically applies a layer when the previous layer is frozen. This device counts the number of freezing degree-hours and opens a valve or triggers a pump when the prescribed number of freezing degree-hours is satisfied. This sludge application sequence is repeated until all the sludge is applied or the depth of frozen sludge has reached the design depth of 1.5 m. At no point during this phase should it be necessary for the operator to venture outside to perform operation and maintenance.

By October, all sludge to be dewatered will be frozen and the thawing period will begin. All sludge applications would be stopped and the meltwater drain valve would be opened. To prevent odors, it is impor-

tant to drain the meltwater as soon as possible. This meltwater would be returned back to the head of the plant for treatment because it still contains pollutants such as dissolved organic matter. The impact of this meltwater on the treatment process should not be significant because it is a relatively small volume in comparison to the raw wastewater flow. There should only be a few centimeters of dewatered sludge left in the bed when draining is complete. For example, only 13 cm remained after freezing and thawing 1.0 m of aerobically digested sludge in a pilot scale freezing bed (Martel and Diener 1991).

The final operation would be to remove the dewatered sludge and pack it into tri-wall containers. According to the proposed schedule, this would be done in February. Normally, the ship departs McMurdo for the U.S. on or about 10 February. This means that all the sludge must be removed from the bed and loaded into tri-wall containers within 10 days. This should not be a problem if the operator uses a front-end loader. At Fort McCoy, Wisconsin, this took about 1 hour. Also, the loader operator was able to remove the sludge layer without taking much of the sand with it. Thus, only a small amount of new sand was needed to replenish the sand drainage layer.

ESTIMATED COST

The estimated capital cost of the freezing bed alternative is $301,191 (Table 2). This estimate was developed using the unit costs shown in the CTE (1999) report. Not included is the cost of a sludge storage tank. In comparison, the estimated cost of the 1.0-m belt press alternative is $476,000.

The estimated annual operation and maintenance cost of the freezing bed alternative is $1706 (Table 3). According to the CTE report, the estimated annual operation and maintenance cost of the proposed 1.0-m belt press is $72,102. This is a significant difference that is attributable to the freezing bed requiring very little labor and energy to operate. Natural freeze–thaw is used as the dewatering process rather than mechanical energy and chemicals.

CONCLUSION

A preliminary design analysis indicates that all of the sludge produced by the proposed extended aeration wastewater treatment plant at McMurdo could be dewatered in a 10- by 16-m by 2-m-deep freezing

Table 2. Estimated capital cost of sludge freezing bed at McMurdo, Antarctica.

			Material		*Labor*			
Item	*Units*	*No.*	*Unit cost*	*Total cost*	*Unit cost*	*Exterior*	*Interior*	*Total*
Site work	CY	500	$5	$2,500	$10	$5,000	—	$7,500
Concrete (Including building shell, precast floor, precast foundation)	ft^2	1,722	$72	$123,984	$18	$30,996	—	$154,980
Plumbing	ft^2	1,722	$2.25	$3,875	$2.38	—	$4,098	$7,973
Sump Pump		1	$1,000	$1,000	—	—	$300	$1,300
Sand	ton	48	$11	$528	$10	—	$480	$1,008
Subtotal	—	—	—	$131,887	—	$35,996	$4,878	$172,761
Antarctic multiplier Interior work-35% Exterior work-75%	—	—	—	—	—	$26,997	$1,707	$28,704
Subtotal	—	—	—	—	—	—	—	$201,465
Contractor OH&P* at 15%	—	—	—	—	—	—	—	$30,220
Subtotal	—	—	—	—	—	—	—	$231,685
Contingency at 30%	—	—	—	—	—	—	—	$69,506
Total	—	—	—	—	—	—	—	$301,191

*Overhead and profit.

Table 3. Annual operation and maintanence cost estimate for sludge freezing bed at McMurdo, Antarctica.

Item	*Units*	*No.*	*Unit cost*	*No. of operators*	*Time (hr/yr)*	*Labor rate ($/hr)*	*Annual cost*
Replacement sand (20%)	ton	9.6	$11	—	—	—	$106
Annual sludge removal and loading into tri-walls	—	—	—	2	24	$25	$1200
Replace and regrade sand layer	—	—	—	2	8	$25	$400
Total	—	—	—	—	—	—	$1706

bed. The estimated capital cost of the bed is $301,191, which is 37% less than the proposed belt press alternative. The annual O&M cost of the freezing bed is $1706, which represents a 98% savings over the belt press. In light of this analysis, NSF should consider freezing bed technology as a viable alternative to a belt press for sludge dewatering in McMurdo.

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REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YY)*
February 2001

2. REPORT TYPE
Technical Report

3. DATES COVERED *(From - To)*

4. TITLE AND SUBTITLE

Design of Freezing Bed for Sludge Dewatering at McMurdo, Antarctica

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)

C. James Martel

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

U.S. Army Engineer Research and Development Center
Cold Regions Research and Engineering Laboratory
72 Lyme Road
Hanover, New Hampshire 03755-1290

8. PERFORMING ORGANIZATION REPORT NUMBER

ERDC/CRREL TR-01-3

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

National Science Foundation
4201 Wilson Boulevard
Arlington, VA 22230

10. SPONSOR / MONITOR'S ACRONYM(S)

11. SPONSOR / MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION / AVAILABILITY STATEMENT

Approved for public release; distribution is unlimited.
Available from NTIS, Springfield, Virginia 22161.

13. SUPPLEMENTARY NOTES

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Freezing bed   Sludge dewatering
McMurdo waste treatment   Sludge freezing

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON / 19b. TELEPHONE NUMBER *(include area code)*
U	U	U	U	14	